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# Multi-Material BESO Topology Optimization for SynRM based on printed FeSi6.5%

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**This paper presents a design methodology for electric machines (EM). It is based on discrete multi-material topology optimization (TO) and printed material characteristics. Our methodology uses the Bi-directional Evolutionary Structural Optimization (BESO) heuristic for optimization, and to maximize EM torque, we propose a reformulated problem to accelerate simulation time. It permits considering both ferromagnetic materials and permanent magnets with discrete variables. Printed material characteristics are taken into account, considering several process parameters. A comparison of the final designs for different BH curves is presented.**

*Index Terms*—Electric machines, magnetic materials, printed ferromagnetic, optimization methods

## I. INTRODUCTION

**A**DDITIVE manufacturing technologies offer the flexibility to fabricate complex geometries from several materials, including ferrous ones. It presents a unique opportunity for new concepts designed for electrical machines. On the other hand, Topology Optimization (TO) is the design approach for finding optimal single or multiple materials distribution without requiring the designer’s intuition and can lead to unique geometries. Several approaches have been used to design electrical machines (EM) through discrete TO or continuous methods [1]. While usual multi-material topology optimization is formulated using a density-based method, this paper proposes a novel method to determine magnets distribution discretely. The main advantage of the proposed methodology is that no “gray” materials are created, and the manufacturing of the machine with the proposed distribution of magnets can be realistically considered. Determining the average torque by calculating its instantaneous values can be very expensive. This paper’s proposed methodology improves the average torque density while formulating a cost function based only on two Finite-Elements calculations; No re-meshing is needed. Finally, for ferromagnetic material, we propose to characterize printed material and determine the optimal design for each one. The variation in the BH curve of the printed FeSi6.5% is a printed characteristic function. It will be detailed in the final paper.

## II. DESIGN OBJECTIVE OF ELECTRICAL MACHINE

Permanent magnet motors are known for their excellent performance and compactness. In industrial applications, rare earth permanent magnets present two significant limits to their use environmental and economic. The research interest in the ferrite-assisted synchronous Reluctance Machine (SynRM) has grown in the last decade. The design of these electrical machines through topology optimization has been addressed through NGnet method [2] and gradient-based methods [3].

Generally, this formulation is considered while adopting the average torque based on instantaneous calculation or considering iron losses through Bertotti or Steinmetz formulation. Historically, when considering SynRM, the optimization is based on two essential factors, the motor torque index (1) and the saliency ratio (2). To design flux barriers according to the geometric parameters, several variables have to be determined based on extensive knowledge in EM design.

$$\text{Torque}_{index} = L_d - L_q \quad (1)$$

$$\text{Saliency}_{ratio} = \frac{L_d}{L_q} \quad (2)$$

with,  $L_d$  and  $L_q$  the inductance respectively in d and q axis. To address this problem through topology optimization, we propose to formulate an objective function based on the ratio of the energies in both d and q axis for a fixed stator. This way, the obtained flux barriers are of “Fluid-shaped” type, where the shape follows the natural propagation of the stator flux lines in a solid rotor [4].

## III. DESIGN METHOD

### A. Electrical machine model

A three-phase electrical machine is considered, and the number of pole pairs equals two. The current distribution is given in figure 1. The load angle is determined for maximum torque value after optimization for a current density of  $10 \text{ A/mm}^2$ . For the design space, printed materials with different characteristics were used to determine the best barrier shape. The 2D magnetostatic problem (3) is solved on Matlab, and the mesh is generated using GMSH. Two simulations were done to determine magnetic energy  $W$  in  $d$  and  $q$  axis, the first one with a load angle of  $0^\circ$  and the second for a load angle of  $90^\circ$ . The B-H curve of different printed materials [5] are approximated by a Frohlich-Kennelly model, as presented in

Fig. 2. The anhysteretic curve is deduced, approximated by the Marrocco equation and introduced in the FE model.

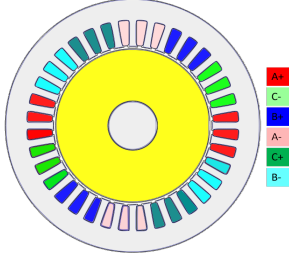


Fig. 1. Electrical machine with 36 slots

$$-\nabla \cdot (\nu \nabla A_z) = J_z + \nabla \cdot \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} M \quad (3)$$

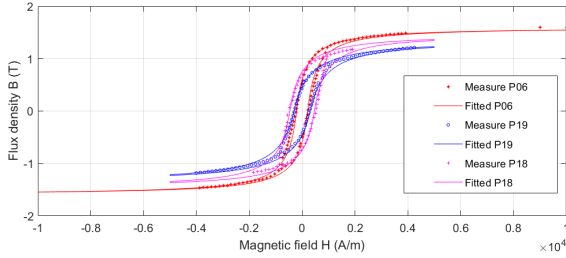


Fig. 2. B-H curves of the measured samples and fitted Frohlich-Kenelly model

### B. Optimization problem

The optimization problem is solved firstly to determine barriers distribution, and a second optimization is done to deduce magnets distribution. In (4), we present the first problem with  $V_e$  the elementary volume of a mesh and  $N_{iron}$  the total number of mesh elements. The detailed algorithm will be presented in the final paper. Bi-directional Evolutionary Structural Optimization (BESO) [6] is used for TO. The magnetization magnitude can be considered a discrete variable, and we deduce the magnetization direction as normal to the flux density distribution  $B$  in the rotor.

$$\begin{aligned} \max_{\rho_e} \quad & 1 - \frac{W_q}{W_d} \\ \text{s.t.} \quad & \sum_{i=1}^{N_{iron}} \rho_e \cdot V_e = V_{iron} \\ & \rho_e = 0 \text{ or } 1 \quad e = 1 \cdots N_{mesh} \end{aligned} \quad (4)$$

## IV. RESULTS

Optimized designs are given for P06 and P18 materials for a fixed volume  $V_{iron}$  at 55% in Fig. 3. The barriers number remains constant, but their shape is adapted to the considered material. The mean torque is determined by Arrkio's and is presented as a function of the load angle in Fig.5. The maximum torque is reached for the same angle. In this case, the model is saturated, and the load angle is higher than  $45^\circ$ . The second optimization considers the design domain as the flux barriers. The same problem as in (4) is solved, but only for

magnets. The result is presented for combining P06 material and ferrite magnets with a volume of 50% of the flux barriers in Fig. 4.

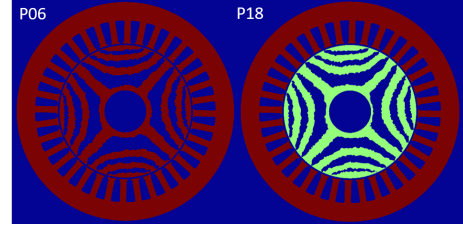


Fig. 3. Optimized geometries for P06 and P18 materials

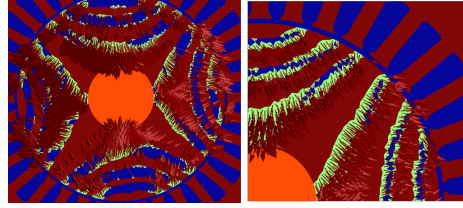


Fig. 4. Distribution of magnets in flux barriers

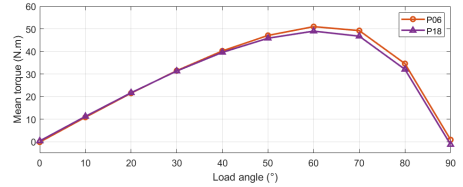


Fig. 5. Simulated mean torque at different current angles

## V. CONCLUSION

In this paper, a novel TO methodology is presented. It considers printed material characteristics combined with an adapted formulation of the objective function for SynRM, and accounts for multi-material based on bi-level BESO optimization. For varying printed materials, the final solution presents varieties in the geometry but leads to close optimal torque.

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